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A Case History of Effective Fishery Management: Chesapeake Bay Striped Bass

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Abstract.—Stocks of anadromous striped bass *Morone saxatilis* of the Atlantic coast have supported important fisheries since colonial times. Commercial landings reached a record high in 1973, then declined by almost 90% during the following decade. Juvenile production by the Chesapeake Bay stock, a major contributor to coastal fisheries, was depressed during the 1970s. These patterns prompted efforts to identify why striped bass had declined and to rebuild the Chesapeake Bay stock. We review the history of the striped bass decline and the science, management, and legislation that led to its recovery. Historical data and modeling results indicated that recruitment overfishing was a major factor in the decline. Juvenile production may have been further depressed by water quality problems that reduced survival of early life stages. Mathematical models demonstrated that reducing fishing mortality would immediately increase population growth rate, regardless of the decline's cause. An Interstate Fishery Management Plan (the Plan) was adopted by the Atlantic States Marine Fisheries Commission in 1981 and amended in 1985 to protect females until 95% could spawn at least once, thus increasing age at entry from 2 to 8 years. The Plan was strengthened in 1984 by the Striped Bass Conservation Act (Public Law 98-613), which required states to comply with the Plan or submit to federal moratoria. In 1985, states imposed moratoria or began a progressive increase in minimum size limits scheduled to reach 97 cm (38 in) in total length by 1990. Hatchery-reared striped bass were stocked in the Chesapeake Bay beginning in 1985 and may have accelerated recovery, though the benefits of stocking were far outweighed by the benefits of reducing fishing mortality. Abundance of females on spawning grounds in Maryland doubled between 1985 and 1988, and recruitment began to improve in 1989. Coastwide recreational catches increased more than 400% between 1985 and 1989. Regulations were relaxed in 1990 and an adaptive management scheme was adopted to allow limited harvest while the stock continued to recover. Recruitment continued to improve and the Chesapeake Bay stock was declared fully recovered in 1995, 10 years after stringent management measures were implemented.

Many economically important fish stocks have suffered serious overexploitation (Anthony 1990; Nehlsen et al. 1991; NEFSC 1993; NMFS 1993; Rosenberg et al. 1993; Sissenwine and Rosenberg 1993; Murawski et al. 1997), yet attempts to avoid or correct stock depletion through resource management often have been hamstrung by opposition from fishers, reluctance of managers to make politically difficult decisions, and scientific uncertainty (Ludwig et al. 1993; Sissenwine and Rosenberg 1993). Here we report an apparent fishery management success and document the combination of science, management, legislation, and politics that made it possible.

Atlantic Striped Bass *Morone saxatilis*

The striped bass *Morone saxatilis* has been important to communities of the Atlantic coast of the USA since colonial days. In 1670, the first public school in the New World was partially funded by taxes on the sale of striped bass (Pearson 1938). Three centuries later, striped bass fisheries from Maine to North Carolina provided more than US$200 million in economic output (USDOI and USDOC 1984).

Striped bass of the middle Atlantic coast are anadromous, spawning in brackish to freshwater reaches of estuaries (Merriman 1941; Raney 1952). Most anadromous striped bass live in estuarine waters for the first several years of life, then migrate to coastal waters to feed and overwinter (Merriman 1941; Raney 1952). In spring, mature bass return to brackish or freshwater reaches to spawn, probably in natal areas (Mansueti 1961; Nichols and Miller 1967). Striped bass are iteroparous and can live about 30 years (Merriman 1941).

Anadromous populations of striped bass spawning in Chesapeake Bay and the Hudson River are the primary contributors to Atlantic coastal fisheries (Berggren and Lieberman 1978; Wirgin et al.

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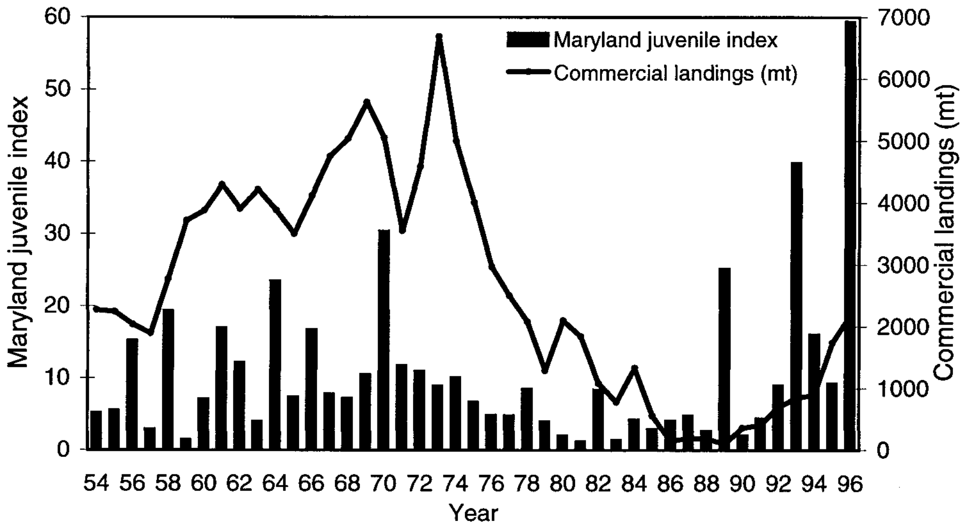

FIGURE 1.—Indices of juvenile striped bass abundance for Maryland's waters of Chesapeake Bay and commercial landings (metric tons [mt], North Carolina through Maine) of striped bass, 1954–1996. The juvenile index is the mean number of age-0 striped bass caught in beach seine hauls in Maryland nursery areas and has been shown to predict subsequent landings (Goodyear 1985). Sampling methods have been consistent over time; however, the number of sampling locations increased in 1962 and in 1966. No other changes have occurred since 1966 (Rago et al. 1995). Sources: juvenile indices—MDNR (1995); H. Hornick, Maryland Department of Natural Resources, personal communication; commercial landings—Boreman and Austin (1985); USDOI and USDOC (1996).

1993). The Chesapeake Bay stock is thought to be the most productive Atlantic coast stock (Merriman 1941), and has contributed as much as 90% to Atlantic coastal landings (Van Winkle et al. 1988). However, coastal stock composition varies depending on year-class strength, location, and season, and the Hudson River stock can make up a significant proportion of the coastal stock in some years (Fabrizio 1987; Van Winkle et al. 1988). The Hudson River stock's primary contribution to the coastal population is north and east of the Hudson River (Waldman et al. 1990; Dorazio et al. 1994). Two additional stocks spawning in the Delaware River and Roanoke River probably make only minor contributions to contemporary coastal fisheries. The Delaware River stock has been unproductive for most of the 20th century (Chittenden 1971), though it is now recovering as water quality there improves (Albert 1988; USDOI and USDOC 1994). The Roanoke River stock appears to be less migratory than the other anadromous stocks (Hassler et al. 1981; Boreman and Lewis 1987; Haeseker et al. 1996).

The postcolonial history of Atlantic striped bass suggests a long, gradual decline punctuated by intermittent periods of high productivity (Raney 1952; Koo 1970). As early as the mid-1700s, concerns were expressed regarding scarcities of striped bass caused by ''very great numbers having been imprudently, or rather *wantonly* taken in one season'' (Tenney 1795). A steeper downward trend appears to have begun during the late 19th century, probably due to habitat destruction (dam building, pollution) and fishing pressure (Pearson 1938; Raney 1952). Commercial landings of striped bass reached an historic low during the 1930s, raising concerns about the future of the fishery (Koo 1970). Landings rebounded after the appearance of the dominant 1934 year-class in Chesapeake Bay (Merriman 1941; Koo 1970) and continued to increase until the 1970s (Koo 1970; Boreman and Austin 1985). Between 1954 and 1970, strong year-classes were produced in Chesapeake Bay approximately every 2–4 years (Figure 1). An exceptionally large year-class was spawned in 1970, and commercial landings reached an historic high of 6,700 metric tons in 1973 (Boreman and Austin 1985; Richards and Deuel 1987). However, strong year-classes failed to appear in Chesapeake Bay after 1970, and commercial landings declined to less than 1,000 metric tons by 1983 (Figure 1). This decline alarmed fishers, managers, and scientists (Boreman and Austin 1985; Goodyear et al. 1985) and prompted significant new research and conservation efforts focused on the Chesapeake Bay stock.

Interjurisdictional Management

No comprehensive management plan existed for Atlantic striped bass before 1981, although many states had promulgated their own regulations during the 1940s. These typically included minimum size limits of 25–30 cm (10–12 in) south of New Jersey and about 41 cm (16 in) to the north (ASMFC 1990). While providing some protection, such size limits were far below the size at 50% female maturity (Merriman 1941; Berlinsky et al. 1995) and could not preserve spawning stocks under heavy fishing pressure (USDOI and USDOC 1990). The long-distance migrations of striped bass created a political impediment to further restrictions because states with strong conservation measures would lose the benefit of their efforts to states with less restrictive management.

The need for cooperative management prompted the Atlantic States Marine Fisheries Commission (ASMFC) to develop and adopt an Interstate Fisheries Management Plan for the Striped Bass (the Plan) in 1981 (ASMFC 1981). The Plan called for minimum size limits of 36 cm (14 in) total length (TL) in bays and estuaries and 61 cm (24 in) TL on the coast, and it recommended spawning area closures during the spawning season. The recommendations were adopted by most states and jurisdictions during 1981–1984; however, the ASMFC recognized that these measures were insufficient to bring about recovery of the Chesapeake Bay stock.

The ASMFC amended the Plan three times during 1984 and 1985 to further restrict fishing (Weaver et al. 1986; Ballou 1987). The first two amendments set targets for reducing fishing mortality and allowed the states to propose methods for meeting targets. The third amendment was more specific and focused on protecting the Chesapeake Bay's 1982 year-class. This year-class was only average in size but was the strongest since the Plan had been implemented. Amendment 3 recommended that the states protect 95% of females of the 1982 and later year-classes until 95% had an opportunity to spawn at least once. This required the states to either institute moratoria on fishing or progressively increase minimum size limits to exceed the 95th percentile for size of females at the age of 95% maturity. Although females begin to mature at age 4, the best available estimates of maturation rates indicated that 95% maturity of a cohort may not be achieved until age 8 (USDOI and USDOC 1990). The 95th percentile for size of females at age 8 was estimated to be 97 cm (i.e., 95% of females would be smaller than 97 cm). Thus size limits were required to be increased to 97 cm (38 in) TL by 1990. Maryland and Delaware declared moratoria on striped bass harvest in 1985, and Maryland also prohibited sales (Weaver et al. 1986). Other jurisdictions adopted increasing size limits starting in 1985. These were essentially closures since few fish in the stock exceeded the size limits.

The ASMFC's adoption of strong conservation measures was a milestone in the effort to restore Chesapeake Bay striped bass. Also crucial, however, was the Atlantic Striped Bass Conservation Act (Conservation Act, Public Law [P.L.] 98-613 and its successors), first passed by the U.S. Congress in 1984. This Act greatly strengthened the ASMFC's position by stipulating that a federal moratorium on striped bass fishing would be imposed on any state or jurisdiction not in compliance with the Plan. The ASMFC does not have regulatory authority, thus its Plan was only a management recommendation that the states could ignore without legal consequence. The Conservation Act also ensured equitability: since all states must comply, all would share in the hardships of severe restrictions. Given the political and economic unpalatability of Amendment 3, all states would not have fully complied without the impetus of the Conservation Act. Federal moratoria were threatened several times and implemented once under the Conservation Act before regulations were brought into compliance with the Plan (Ballou 1987; USDOI and USDOC 1992).

An additional act of Congress became important in supporting striped bass management. The ''Emergency Striped Bass Study'' (the Emergency Study, P.L. 96-118) was established by Congress in 1979 to monitor the status of striped bass stocks and determine why the Chesapeake Bay population had declined. During the 1970s monitoring efforts were sporadic, fishing mortality rates poorly known, the status of the spawning stock unclear, and reasons for the decline not understood. The Emergency Study provided funding, federal oversight for a coordinated research program, and impetus for states to augment research with funding from other sources. The result was a major expansion of striped bass research and monitoring along the Atlantic coast at a time when a major management experiment was about to begin.

Population Monitoring

Before the 1980s, fishery-independent monitoring of striped bass was limited to juvenile surveys conducted in New York, Maryland, and North Carolina jurisdictional waters. Virginia had begun a juvenile survey in 1967 but discontinued it after 1973. Spawning stocks had been sampled intermittently; however, consistent programs for sampling spawning stocks and the coastal migratory population had not been developed. Sampling of commercial landings was inadequate for biological characterization.

Funding from the Emergency Study supported juvenile surveys in the Delaware River, in Virginia nursery areas, and in the Hudson River. Spawning stock sampling was initiated in Chesapeake Bay and the Hudson River, and a program was established for monitoring the coastal stock during its fall migration. Fishery-dependent monitoring was expanded in many states to improve fishery statistics and biological characterization of landings. Tagging studies were begun to monitor fishing mortality and examine population processes such as growth and age-specific migration (e.g., Dorazio 1993; Dorazio et al. 1994). Female maturation schedules were reevaluated (Berlinsky et al. 1995) to refine Amendment 3 and provide input for models predicting population response to management.

Causes of the Decline

When the Emergency Striped Bass Study began, three broad hypotheses were formulated to explain the decline of the Chesapeake Bay stock (USDOI and USDOC 1982): (1) habitat degradation, including toxic contaminants, changes in water quality from agricultural and sewage treatment practices, unfavorable environmental conditions, and altered water flow patterns; (2) changes in ecological interactions—for example, increases in starvation, predation, competition, or disease; and (3) overfishing.

Testing hypotheses was difficult because striped bass populations were depressed, several interacting factors could be involved, and the problem was retrospective, requiring demonstration of historical change in processes. For example, laboratory experiments clearly demonstrated toxic effects of low pH to striped bass larvae and juveniles (Buckler et al. 1987) but could not address whether there had been a decreasing pH trend in spawning rivers or an increase in the frequency of low pH events during the period of the 1970s decline. Data sets from the 1970s revealed no statistically significant ($P < 0.10$) change in the frequency or magnitude of extreme pH events (pH < 6.5) on striped bass spawning grounds. However, power analysis showed that only very large changes in pH events could have been detected (Janicki et al. 1986). Research of the 1980s could reveal the potential importance of a factor but, without adequate historical data, could not directly evaluate its role in the decline.

Hypotheses concerning water quality were addressed through laboratory and in situ bioassays coupled with water quality monitoring. In laboratory experiments, early life stages of striped bass were exposed to a mixture of organic and inorganic contaminants at 0.25–4 times estimated environmental concentrations in spawning areas of Chesapeake Bay (Mehrle et al. 1987). Salinity of dilution water was 0, 2, or 5‰—within the range naturally encountered by larvae and juveniles (Rathjen and Miller 1957; Polgar et al. 1976; Setzler-Hamilton et al. 1981). Larvae in saline water (2–5‰) survived the contaminant mixture at up to four times the estimated environmental concentrations but died at 0‰ salinity. Salinity had similar ameliorating effects on pH toxicity (Buckler et al. 1987). Larvae exposed to pH less than or equal to 6.0 in freshwater died rapidly; however, survival was high at the same pH in 5‰ salinity. Prolarval striped bass were more sensitive to contaminant mixtures and pH than were eggs or later life stages (Hall et al. 1984; Buckler et al. 1987).

In situ bioassays using prolarvae were conducted in four major Chesapeake Bay spawning areas in Maryland during 1984–1990 (Hall 1991; Rago 1991; Hall et al. 1993) and in four Virginia spawning areas in 1989 and 1990 with similar methods (Finger et al. 1998). Flow-through test chambers (68 L) containing 500 prolarvae were suspended in river water and sampled every 24 h for 4 d to estimate larval survival. Identical test chambers were suspended in tanks filled with contaminant-free water to serve as controls on shore. Additional bioassays were conducted in an ''on-site'' laboratory to examine dose–response relationships and to increase replication. Prolarvae (1 or 10 individuals) were held in flow-through containers (250 mL or 1 L) and exposed to river water at a range of dilutions or to contaminant-free water (controls). Concurrent with bioassays, in situ water quality was monitored for organic and inorganic contaminants as well as temperature, salinity, dissolved oxygen, pH, conductivity, and hardness.

The in situ and on-site bioassays revealed intermittent toxicity of environmental conditions to striped bass larvae. Larval mortality varied spatially and temporally and appeared to be related to ambient concentrations of contaminants (particularly aluminum and other metals), acidic conditions, buffering capacity of the watershed, possible point source contamination, and natural climatic events (Hall et al. 1993). The Nanticoke River is a poorly buffered watershed with relatively high levels of dissolved aluminum, and larval mortality was generally high. The Choptank and Potomac Rivers showed elevated levels of aluminum and other metals, and generally had high larval mortality. In contrast, larval mortality was low in the upper Chesapeake Bay in all years and in the Virginia tributaries tested in 1989 and 1990 (USDOI and USDOC 1992; Finger et al. 1998). Concentrations of toxic contaminants were low in the upper Chesapeake Bay and Virginia rivers, and the water in the upper Chesapeake Bay was slightly saline.

Episodic climatic events caused severe mortality in the bioassays on several occasions. An acidic rainfall in 1988 reduced pH in a Nanticoke River nursery area from 7.2 to 6.1 within 8 h. The pH returned to normal within 24 h, but during the pH depression mortality of larvae held in river water was 100%. Control mortality was only 10% (Finger et al. 1998). Similar catastrophic mortality was observed in the Potomac River after sudden drops in water temperature (Hall et al. 1993).

Synthesis of seven years of contaminant and water quality studies suggested that water quality problems existed in some spawning areas, with the potential to depress larval survival. However, results from the upper Chesapeake Bay supported the argument that chronic water quality problems were not the sole cause of the problem. Juvenile abundance indices remained low in the upper Chesapeake Bay despite consistently high larval survival rates.

Evaluating the importance of ecological factors such as predation, competition, and disease was difficult because striped bass were scarce and time series of retrospective data did not exist. Laboratory and field studies identified numerous potential fish and invertebrate predators on early life history stages of striped bass (McGovern and Olney 1988); however, stomach content studies yielded no evidence of natural predation on striped bass eggs or larvae (Martin and Setzler-Hamilton 1982; Kahnle and Brandt 1984; McGovern and Olney 1988). Measurements of nutritional state of field-caught striped bass larvae in the Potomac River and Choptank River suggested that nutritional stress could have contributed to poor recruitment during 1981–1985 (Setzler-Hamilton et al. 1987). Mean growth rate of larval striped bass was positively correlated with total prey density, cladoceran (a preferred prey) density, and temperature the previous week (Martin et al. 1985). Despite such results, studies of starvation were inconclusive because synoptic, long-term records of zooplankton composition and abundance did not exist to show whether prey availability had changed during the decline.

Studies of disease focused on infectious pancreatic necrosis (IPN), a viral disease of salmonids that was identified in hatchery striped bass during spring 1983 (Schutz et al. 1984). Resistance of striped bass larvae, juveniles, and adults to IPN virus was tested under normal and stressful environmental conditions. These studies consistently showed that striped bass could be carriers of the disease yet be nonsymptomatic even under stressful pH and temperature conditions (Wechsler et al. 1987b). The virus was not transmitted between generations of striped bass, either from experimentally infected parents to gametes or from experimentally infected gametes to larvae (Wechsler et al. 1987c). No evidence was found of IPN virus infection of wild Chesapeake Bay striped bass (Wechsler et al. 1987a).

Overfishing was evaluated as a contributor to the decline by examining trends in fishing effort, changes in landings composition, fishing mortality estimates, and results of mathematical modeling. Evidence to test for directional trends in fishing effort during the 1970s was sparse; however, any trend was probably an increasing one. Fishing effort in the recreational sector increased during the 1960s and 1970s (Merriner 1976; Florence 1980), and efficiency of fishing effort increased as well with improvements in electronics, small boat design, and communications (Florence 1980). The recreational fishery was responsible for at least half of the striped bass harvest during the 1970s (Richards and Deuel 1987). Technological advances similarly would have increased effective effort in commercial fisheries. Regression models predicting landings from recruitment indices indicated that mean age of fish in Maryland's commercial landings declined between 1964–1973 and 1974–1983, implying an increase in total mortality between the two time periods (Goodyear 1985a).

The absolute level of fishing mortality that prevailed during the 1970s is poorly known; however, available estimates are very high for a long-lived iteroparous species such as striped bass. In Maryland's waters of Chesapeake Bay, estimated annual fishing mortality of the 1970 year-class was 36% for females at age 6 and 36–92% for males at ages 4–6 (MDNR 1985). In coastal mixed-stock areas,

TABLE 1.—Summary of research conducted on factors responsible for the decline of striped bass in Chesapeake Bay.

Hypothesis	Research	Conclusions
Contaminants (larvae, juveniles)	*In situ* and on-site bioassays in spawning rivers of Maryland: Nanticoke River 1984–1990, Upper Chesapeake Bay 1985–1990, Choptank River 1987–1990, and Potomac River 1986, 1988–1990	Toxic conditions in some rivers in some years; no single contaminant consistently responsible for mortality, but low pH, trace metals, and temperature drops were suspected factors; survival highest in upper Chesapeake Bay
	In situ and on-site bioassays in spawning rivers of Virginia: Rappahannock River 1989–1990, Mattaponi River 1989–1990, Pamunkey River 1989–1990, and James River 1989–1990	Survival generally high; metals concentrations lower than in Choptank and Nanticoke Rivers
	Laboratory experiments: Effects of pH, aluminum, and metals on larvae, juveniles	Highly sensitive to pH less than 6.0 and to aluminum concentrations; salinity and organic acids ameliorate effects
Starvation (larvae)	Laboratory studies; field surveys	Limited evidence of impact except perhaps in Potomac River
Predation or competition (larvae)	Field surveys; larvae exposed to predators in laboratory	Numerous potential predators but litle field data to test importance
Climatic events	Evaluated historical data on pH trends in major spawning rivers	No evidence of systematic decrease in pH or increased frequency of low pH events; historical data insufficent to detect small changes
Water use practices	Evaluated flow conditions in vicinity of Chesapeake and Delaware Canal	Some evidence for entrainment of larvae and transport out of Chesapeake Bay but impact uncertain
Disease	Laboratory studies of IPN virus; field sampling for infected striped bass	Nonlethal, but striped bass can be carriers; potential disease problems in intensive culture, but not likely in nature
Fishing mortality	Analysis of historical data; simulation modeling; response to management	Strong evidence for recruitment overfishing; difficult to distinguish from effects of other factors.

annual fishing mortality estimates ranged from 30% to 60% per year during the 1970s for ages and sexes combined (ASMFC 1990). Modeling studies showed that mortality required to produce commercial landings of the 1970s also was very high (55%/year; USDOI and USDOC 1990). Biological reference points estimated from population models (see ''Rebuilding Strategies,'' below) predicted stock collapse at annual exploitation rates of 33% at minimum size limits prevailing during the 1970s: 30–36 cm (12–14 in) TL in Chesapeake Bay and 43 cm (17 in) TL along the Atlantic coast (USDOI and USDOC 1990; P. J. Rago, unpublished analyses). Estimated annual fishing mortality for the Hudson River stock, which had not collapsed, varied between 19% and 25% during the 1970s (ASMFC 1990). These lines of evidence strongly suggested that during the 1970s fishing mortality of Chesapeake Bay striped bass had exceeded reference points for stock collapse, and they implicated recruitment overfishing as an important factor in the decline.

Despite the difficulties of testing hypotheses retrospectively, the Emergency Study clarified probable causes of the Chesapeake Bay stock's decline (Table 1). Excessive fishing pressure probably depleted the spawning stock and set the stage for the decline. Reproductive success of the remaining spawners might have been compromised by water quality problems that reduced survival of early life stages. Additional factors could have contributed, but their importance is less clear (e.g., eutrophication; Coutant 1985; USDOI and USDOC 1990).

Recruitment overfishing and episodic poor water quality could have had synergistic effects more disastrous than either alone. Survival of eggs and larvae depends on the occurrence of adequate environmental conditions during at least part of the spawning season. If favorable conditions occur briefly and infrequently, juvenile production depends on the number of eggs and larvae in the water during favorable periods. If overfishing reduced the number of mature fish and truncated the age composition of the spawning stock, this might have reduced the duration of the spawning season and the number of eggs produced because older fish appear to spawn earlier than younger ones (Hollis 1967). With spawning concentrated in a shorter time period, a catastrophic mortality event potentially could kill a larger proportion of a given year's spawn. An additional effect of truncated age structure could have been to reduce viability of the spawn. Younger females not only produce fewer eggs than older ones, but their eggs are less viable as well (Monteleone and Houde 1990).

Rebuilding Strategies

Developing Management Strategies

The strong influence of environmental variation on striped bass recruitment was well known before the 1980s (Ulanowicz and Polgar 1980; Dey 1981; Kernehan et al. 1981; Kohlenstein 1981), but the consequences of recruitment variability, additional variability from anthropogenic sources, and age-specific migration were only partially understood. To address these issues, the basic techniques of Leslie matrix models (Leslie 1945) were adapted for assessment of Chesapeake Bay striped bass (Cohen et al. 1983). These and subsequent models played an important role in analyzing options for rebuilding strategies.

Early modeling studies had demonstrated that growth overfishing was occurring, thus fishing mortality should have been reduced and size limits increased (Goodyear 1984; Goodyear et al. 1985). However, size limits that maximized yield would also severely disrupt historical fisheries and yield allocations (Goodyear 1984). The same allocation problems existed for addressing recruitment overfishing. To examine population growth rates and allocation patterns under alternative management regimes, a series of population models was developed (Goodyear 1978, 1984, 1985b, 1988; Cohen et al. 1983; Goodyear et al. 1985). The models incorporated sex, size, and age structure of the population, stochastic recruitment, and migration between Chesapeake Bay and coastal populations. A general matrix version was subsequently implemented so that population growth rates and yield allocation under different seasonal and area closures and size limits could be solved directly (ASMFC 1990). These projection models suggested that fishing mortality (F) targets of $F = 0.25$ and $F = 0.5$ were needed for stock rebuilding and stock maintenance, respectively (assuming natural mortality, M, $= 0.2$). These rates corresponded to intrinsic rates of increase (r) equal to 0.17 for stock rebuilding and approximately zero ($r = -0.02$) for maintenance. Historical allocation of landings could be preserved if size limits were set at 46 cm (18 in) TL for the Chesapeake Bay and 71 cm (28 in) TL for the coast. An additional model with similar structure but different assumptions provided equivalent estimates of management targets (Crecco 1988; ASMFC 1990).

The projection models were sensitive to input parameters such as migration, maturation, and nonharvest (catch-and-release, bycatch) mortality. Migration rates controlled exposure to region-specific length limits and fishing mortality and thus influenced predicted population growth rates, yield allocation, and fishing mortality targets. Maturation rates influenced estimates of recovery rates. Nonharvest mortality was taken as a fixed fraction (0.20) of fishing mortality because the distribution and magnitude of future fishing effort was unknown. These uncertainties were addressed through sensitivity analyses, and the models provided an essential framework for evaluating potential recovery rates and yield allocation under alternative management schemes. Results indicated that population recovery would require time, because of the high age at full maturity, and favorable conditions, because of the stochastic nature of first-year survival rates. However, reductions in fishing mortality would yield immediate benefits to the stock's reproductive potential, regardless of causes for the decline.

Striped Bass Stocking

Stocking hatchery-reared fish to supplement natural production was part of the rebuilding strategy for the Chesapeake Bay stock. Cooperative agreements among the U.S. Fish and Wildlife Service (USFWS), Maryland, and Virginia led to stocking of 7.5 million fingerling (35–200 mm TL) striped bass into Chesapeake Bay by 17 hatcheries during summer and fall of 1985–1993 (USDOI and USDOC 1994). The agreements required all fish to be marked with binary-coded wire tags and the population to be monitored for tags after stocking. Ninety-four thousand hatchery fish were marked with external tags in addition to coded wire tags. Stocking was to be discontinued when the Chesapeake Bay stock was considered recovered.

Population Response

The response of striped bass stocks to restoration efforts is best revealed by fishery-independent monitoring of Maryland's spawning stocks. This was a comprehensive monitoring program that began 3 years before Amendment 3 was implemented. Sampling was conducted by using an array of randomly arranged drift gill-net meshes (70–178-mm-stretch mesh) fished 5–7 d/week during the spawning season. Additional meshes targeting larger fish were used in 1982 and after 1989 (203-, 229-, and 254-mm-stretch mesh). Data for 1985–1995 were corrected for variation in selectivity with sampling location, fish size, and sex (MDNR 1995). Sampling was not conducted in the Choptank River during 1995; this probably shifted the 1995 averages downward because striped bass catch per unit effort had generally been high in the Choptank River. Age was determined by reading scales; maturity of all fish was verified by expression of gonadal products.

Abundance of male and female striped bass was low on the spawning grounds when the survey began in 1982 (Figure 2). Most females were age 10 or older, survivors from the 1970 and earlier year-classes (MDNR 1985). Males of the 1982 year-class first appeared on the spawning grounds in 1984 at age 2 (mean size, 30 cm; Mansueti 1961) when a significant number would have been mature (Setzler et al. 1980). The 1982 year-class would not have been completely protected from fishing until the 1985 Maryland moratorium, nor would all males in the cohort mature until 1986. Thus the impact of Amendment 3 is better demonstrated as males of the weak but fully protected 1983–1988 year-classes matured as 2- and 3-year-olds (1985–1991) and by the broadening of the age structure, which occurred by the early 1990s (Figure 2).

A similar pattern was seen in the female spawning stock, although delayed by several years because females mature later than males (Bason 1971; Jones et al. 1977; Hoff et al. 1988). Females of the 1982 year-class began to mature and contribute to the spawning stock in 1986. By 1987, the 1982–1984 year-classes were responsible for most of the egg production in the Potomac River and upper Chesapeake Bay (Houde and Rutherford 1992). Older, more fecund females were rare and contributed relatively little to population fecundity after 1987. The age structure of the female spawning stock continued to broaden through the early 1990s (Figure 2) despite the weak year-class strength of the 1983–1988 cohorts (Figure 1).

The results of conservation efforts were observed in other regions as well. The bulk of the coastal mixed stock was composed of protected year-classes by 1987 (USDOI and USDOC 1990). Spawning stock abundance increased in the Hudson River[1] (Figure 3). Recreational catches increased in all areas, and more than 90% of the fish caught were released alive as minimum size limits continued to increase (Figure 4).

Despite improvement in the Chesapeake Bay spawning stock, recruitment indices in Maryland's waters of Chesapeake Bay remained at or near their lowest levels until 1989. In that year, the catch of juveniles was extremely high at one of four stations in the Choptank River, producing a recruitment index (25.2 striped bass/haul) that was then Maryland's second highest on record (Figure 1). Recruitment in other Maryland nursery areas was not exceptional in 1989, but was high in Virginia's waters of Chesapeake Bay.

Reopening the Fishery

The significance of Maryland's high juvenile index in 1989 went beyond its potential implications for recovery of the Chesapeake Bay stock. Amendment 3 of the ASMFC's Plan stipulated that regulations protecting the 1982 and subsequent year-classes would remain in place until the 3-year average of Maryland's juvenile index exceeded 8.0, the approximate long-term average. Although the 1987 and 1988 juvenile indices were low, the 1989 index was sufficiently large to raise the 3-year average higher than 8.0 and initiate a new management regime.

The decision to move to less restrictive management was not easily made, even though the Plan's criterion had been met. The 3-year running average did not consider the precision of annual index values or interannual variability of the indices entering the average. Thus it was possible that regulations could be relaxed after a single annual index of 24, even if the two preceding indices had been zero. Equally serious, a single large catch within an annual survey could cause the threshold to be reached because precision of annual indices was not considered. Both of these shortcomings came into play in 1989. Exceptionally large catches (nearly 600 juveniles/haul) from one location brought the annual index to 25.2 striped bass per haul. The two previous annual indices had been low (4.8 and 2.7 in 1987 and 1988), but the 3-year

[1] The Hudson River stock undoubtedly also benefited from a closure of Hudson River commercial striped bass fisheries after 1975 due to excessive polychlorinated biphenyl (PCB) levels (ASMFC 1990; Fabrizio et al. 1991). The closures were within the Hudson River only, thus the stock continued to be exploited along its coastal range until Amendment 3 was enacted in 1985.

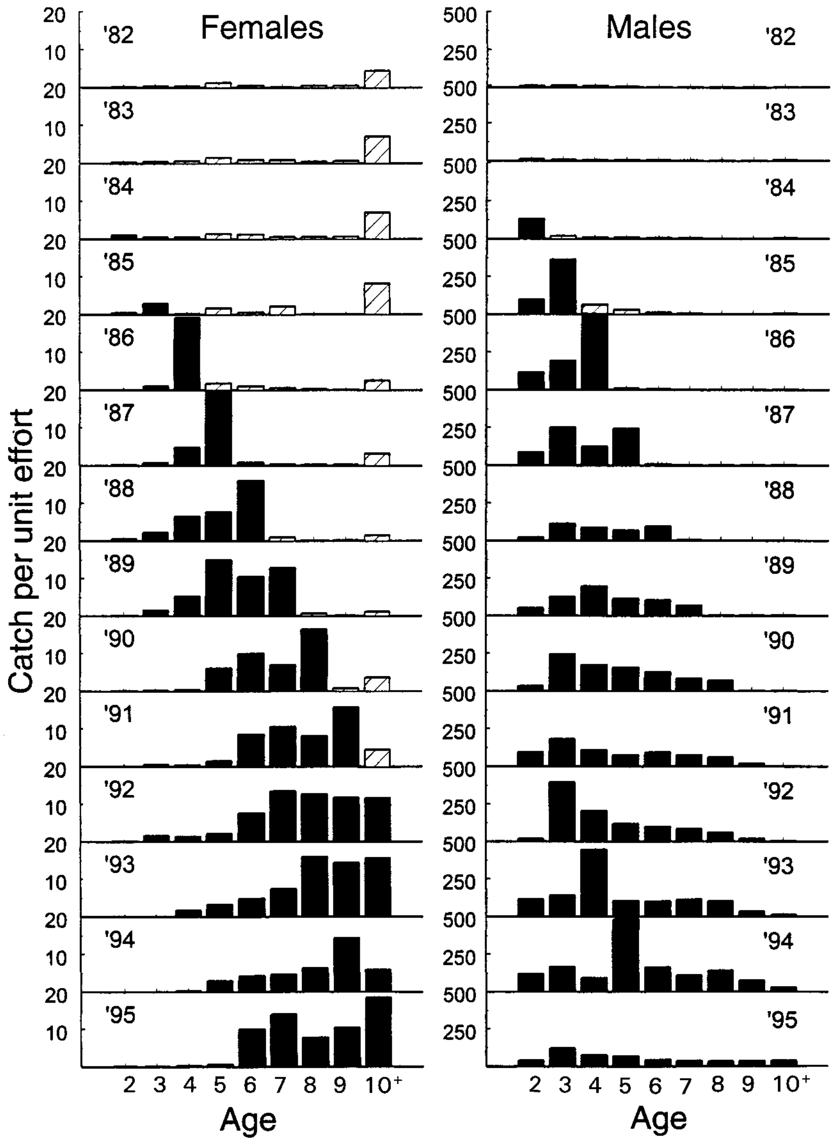

FIGURE 2.—Age-specific abundance indices for male and female striped bass on spawning grounds in Maryland's waters of Chesapeake Bay, 1982–1995. Indices are averages of catch per unit effort (number caught/836 m^2 of gill nets set per hour) in the Choptank River, upper Chesapeake Bay, and Potomac River (Potomac River not sampled 1982–1984, 1994; Choptank River not sampled 1995). The averages are not weighted according to relative size of each spawning area and should be used to examine qualitative trends only. Solid bars = year-classes protected by Amendment 3; cross-hatched bars = unprotected year-classes. The *y*-axis scale differs for males and females. Sources: MDNR (1985, 1995). Data for 1982–1984 were inferred from histograms.

average (10.9) exceeded the management threshold. The ASMFC's Scientific and Statistical Committee recommended delaying reopening but this was politically untenable. The 3-year average was a well-known and clearly understood management trigger and could not be disallowed. Thus after 5 years of de facto moratoria, fishing for striped bass began again in 1990 under a new amendment to the Plan.

Amendment 4 to the ASMFC's Plan was adopted in October 1989. It represented a new, adaptive approach to conservation of Atlantic striped bass (ASMFC 1989). Its basic premise was that striped bass populations must be managed first to restore

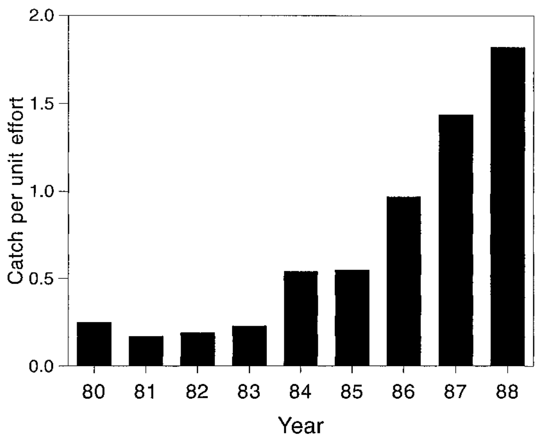

FIGURE 3.—Catch per unit effort (number caught/836 m^2 of gill nets set per hour) of striped bass in the Hudson River gill-net fishery for American shad *Alosa sapidissima,* 1980–1988. The shad fishery coincides with the striped bass spawning season in the Hudson River. Sources: Kahnle and Stang (1986, 1987); USDOI and USDOC (1990).

and maintain spawning stocks and secondarily to provide fishery yield. The objectives were to be achieved by monitoring fishing mortality and adjusting regulations if *F* differed from target levels. Two levels of fishing mortality were identified. The first (F = 0.25) was a restoration level, projected to allow the stock to continue to increase although more slowly than under no exploitation. The second (F = 0.5) was a maintenance level for sustainable fishing of a fully recovered stock. The decision to move from the restoration level to the maintenance level was to be based on several indicators of stock status, including recruitment indices and age composition of the spawning stock.

Under Amendment 4, the states were allowed to relax regulations and prosecute tightly controlled fisheries starting in 1990. Minimum size limits could be reduced to 71 cm (28 in) TL along the coast and to 46 cm (18 in) TL in estuarine producer areas (USDOI and USDOC 1994). Daily bag limits of one or two fish were imposed on the recreational fishery, and some states enforced seasonal closures as well. Maryland adopted a quota system to control its harvest.

The commercial fishery under Amendment 4 was much reduced compared with historical levels. Several jurisdictions made striped bass a recreational-only species, and those that retained commercial fisheries imposed seasonal restrictions in addition to minimum size limits. Commercial fisheries were further limited by harvest caps equal to 20% of each state's landings during 1972–1979. Although not

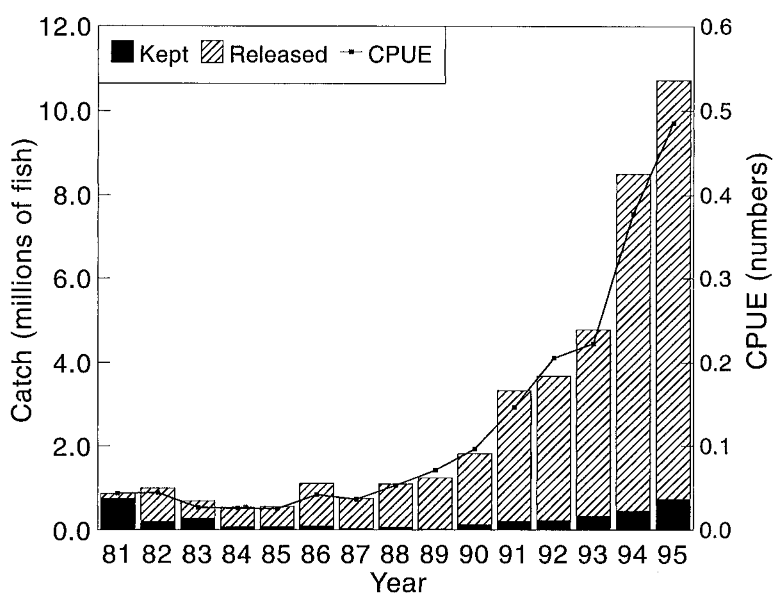

FIGURE 4.—Recreational catch (millions of fish) and catch per unit effort (CPUE) of striped bass along the Atlantic coast from North Carolina through Maine, 1981–1995. The CPUE is the number of striped bass caught per recreational fishing trip along the Atlantic coast. Source: National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Marine Recreational Fisheries Statistics, Washington, D.C., http://www.st.nmfs.gov/st1/recreational/database/index.html.

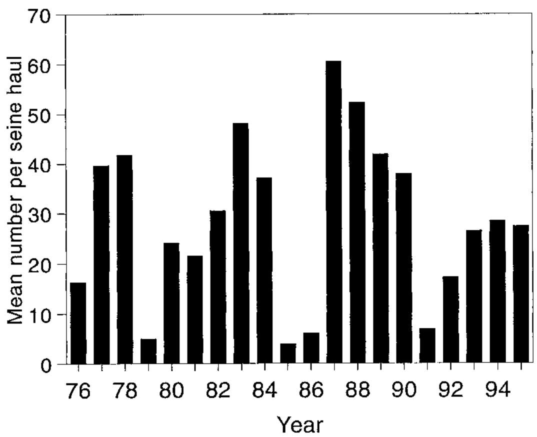

FIGURE 5.—Indices of juvenile abundance for the Hudson River stock of striped bass, 1976–1995. Indices are the mean number of juveniles caught per beach seine haul at standard stations in the Hudson River. Sources: McKown and Young (1992); K. McKown (New York Department of Environmental Conservation, personal communication).

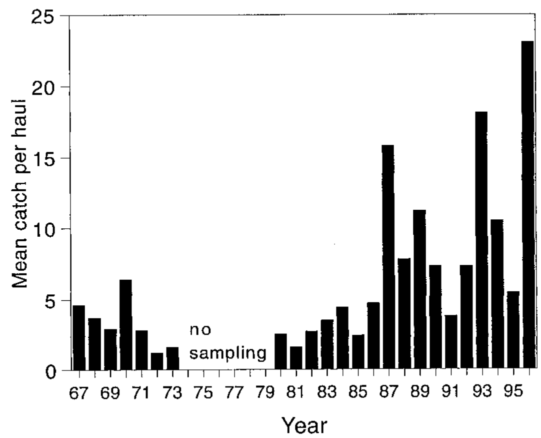

FIGURE 6.—Indices of juvenile striped bass abundance from Virginia's waters of Chesapeake Bay, 1967–1996. Indices are the geometric mean number of juvenile striped bass caught in beach seine hauls in three Virginia tributaries. Survey methods changed in 1980 and 1987, but experiments comparing methods used during 1980–1986 and 1987–present showed no detectable effect on catchability of juvenile striped bass (Colvocoresses 1988). Methods used during 1967–1973 differed little from those used during 1987–present. Sources: Austin et al. (1996); H. Austin (Virginia Institute of Marine Science, personal communication).

required by the Plan, many states closed their commercial fisheries if landings exceeded the cap before the end of the open season. Consequently, about 76% of the annual striped bass harvest was allocated to the recreational fishery during 1990–1993 (USDOI and USDOC 1992, 1993, 1994, 1995).

Amendment 4 required each state to conduct monitoring. States with significant recreational fisheries were required to estimate their recreational catch with a coefficient of variation not to exceed 20%. States with spawning habitat had to conduct spawning stock assessments and juvenile surveys. Most states were required to participate in fishery-independent monitoring or tagging studies used to estimate mortality.

Sustaining Fisheries

Five years of fishing under Amendment 4 were completed at the end of 1994. Fishing mortality levels during 1990–1994 were near the restoration target of $F = 0.25$ (USDOI and USDOC 1995, 1996). Some liberalization of regulations occurred after fisheries reopened in 1990; however, most states voluntarily kept their regulations more restrictive than allowed. Indices of adult stock status showed continued broadening of age structure and increased abundance in many areas (USDOI and USDOC 1994, 1996). Recruitment in Maryland's waters had been poor in 1990 and 1991, renewing concerns that management regulations had been liberalized too soon. However, recruitment rose to average levels in 1992, and exceeded previous highs twice during 1993–1996 (Figure 1). Recruitment was also strong in Hudson River and Virginia nursery areas during 1993–1996 (Figures 5, 6).

The Chesapeake Bay juvenile indices of 1992–1994, improvement in the spawning stock, and other favorable indicators of stock status prompted the ASMFC to declare the Chesapeake Bay stock fully recovered as of January 1995. A fifth amendment to the Plan was then adopted to address management of recovered stocks. The amendment increased the target fishing mortality to an interim level of $F = 0.33$ and an ultimate level of $F = 0.40$ (ASMFC 1995). Amendment 5 broadened the states' options for meeting management goals while retaining the objectives of preventing overfishing and maintaining self-sustaining spawning stocks. During the first year of fishing under Amendment 5 (1995), most states' commercial fisheries harvested less than their quota (Field et al. 1996); however, recreational harvest (retained catch) increased by more than 60% (Figure 4).

Perspectives

Atlantic coast striped bass fisheries of the 1970s and 1980s can be viewed as a large-scale experi-

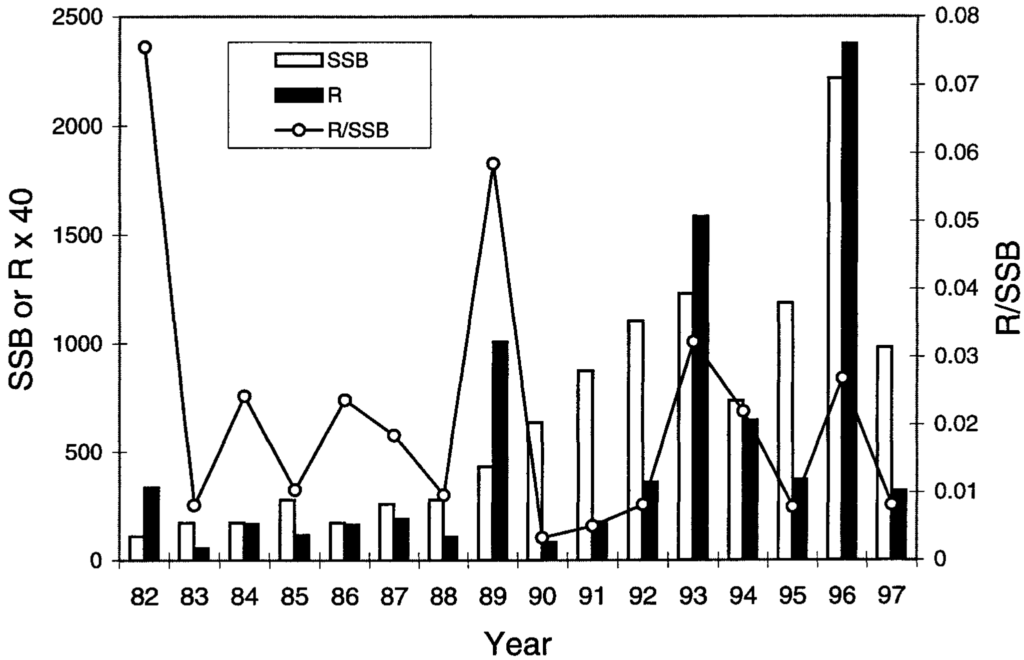

FIGURE 7.—Ratio of recruitment to spawning stock biomass (R/SSB) and indices of recruitment and spawning biomass for striped bass in Maryland (MD) waters of Chesapeake Bay, 1982–1997. Recruitment is the index of juvenile abundance from MD Department of Natural Resources' (DNR's) beach seine survey (as in Figure 1), and SSB is catch per unit effort (number) of mature females on Maryland spawning grounds (as in Figure 2) converted to biomass by using mean length-at-age and length–weight relationships from ASMFC (1990). Data for 1996 and 1997 are from L. Waller, MD DNR, personal communication.

ment in fisheries management. Recruitment overfishing, perhaps coupled with water quality problems, was a major factor in the striped bass decline of the 1970s. Severe harvest restrictions increased reproductive potential of the Chesapeake Bay stock. An improvement in juvenile production occurred after these harvest restrictions were implemented. Here we offer our perspectives on the role of management in the recovery and some of the lessons to be learned from this ''experiment.''

Did the striped bass recovery result from management actions? Recovery of spawning stock biomass and broadening of the age structure occurred after stringent management was imposed, and it seems clear that management can claim credit for rebuilding the adult stock. However, recruitment of striped bass is strongly influenced by environmental factors (Ulanowicz and Polgar 1980; Goodyear and Christensen 1984), and recovery of juvenile production was not guaranteed by recovery of the spawning stock. Conversely, the strong recruitment observed in 1989, 1993, and 1996 could have resulted from a confluence of favorable environmental factors rather than from recovery of the spawning stock. To explore whether increased spawning biomass contributed to increased recruitment, we examined the distribution of recruit per spawning stock biomass ratios (R/SSB) for 1982–1996 from Maryland Department of Natural Resources sampling data (Figure 7). These ratios provide an index of early life stage survival and can be taken to reflect environmental suitability for early life stages. The R/SSB was highest in 1982 and 1989 when SSB was relatively low, suggesting that environmental conditions contributed strongly to recruitment in those years. In 1993 and 1996, R/SSB was above the median, but was 45–65% lower than in 1982 and 1989. The SSB was at its highest levels in 1993 and 1996, and the strongest year-classes in the 44-year recruitment time series were produced, suggesting that high levels of spawning biomass were a major factor in development of the 1993 and 1996 year-classes. These observations provide evidence that restoration of spawning biomass led to improvements in recruitment, thus fishery management can claim some of the credit for recovery of juvenile production by the Chesapeake Bay stock.

The potential to rapidly rebuild the Chesapeake Bay spawning stock depended on stringent conservation measures called for in the ASMFC's 1981 Interstate Fishery Management Plan. However, the Plan alone was not sufficient; political and economic impediments would have prevented many states from adopting the Plan's measures without the catalyst of the Atlantic Striped Bass Conservation Act. The Conservation Act gave authority to the ASMFC Plan and thus ensured that all jurisdictions would share in the sacrifices required by the Plan. Both these aspects were critical to success of the Plan. The concept of the Conservation Act has been extended to all coastal species managed by the ASMFC (the Atlantic Coastal Fisheries Cooperative Management Act, P.L. 103-206; Young-Dubovsky 1993) and has significantly strengthened the basis for interjurisdictional management of U.S. coastal Atlantic species.

Adoption of adequate conservation measures is a fundamental requirement for successful fishery management; however, effectiveness of the adopted measures depends heavily on acceptance by fishers (Healy 1985). Most striped bass fishers were strongly motivated to support conservation efforts because they perceived a crisis in the status of the stock. The Plan provided a focus for this motivation because its measures were easily understood and had intuitive appeal. A strong conservation ethic developed around the goal of protecting females until most could spawn, and compliance with regulations was high. A clearly defined endpoint for restrictive management was also crucial to the Plan's acceptance by fishers. The endpoint was unambiguous and based on a well-known and respected indicator (the MD juvenile index). However, some implications of the endpoint decision rule were not foreseen and it allowed fisheries to reopen under great uncertainty. The qualities that made the decision rule an effective tool for communicating with fishers also made it politically untenable to modify it when it led to risk-prone management actions. Fortunately, Amendment 4 called for a conservative approach to reopening fisheries and served as a safety net to allow continued recovery as exploitation increased.

Hatchery stocking programs are a frequent and popular response to depressed fishery resources. Stocking of striped bass may have enhanced recovery in localized areas of Chesapeake Bay (Appendix). However, analysis of the tradeoffs between reducing exploitation and increasing stocking levels (Appendix) shows that the potential for gains in population recovery were far greater from reducing fishing mortality than from stocking. Stocking may be a useful tool but should not be used as an excuse to avoid conservation when the fundamental problem is overexploitation.

Historical precedence is often invoked as a reason to continue unwise fishery management practices. The example of Atlantic striped bass demonstrates that it is possible to break with long-established patterns; however, the striped bass stock had to be driven virtually to economic extinction before significant changes were made. This is a recurrent problem in fisheries because immediate goals of preserving economic status quo supersede longer-term goals of preserving the resource. The ASMFC and the states adopted a new management regime as the stock recovered. The continuing challenge will be to prevent a return to overfishing if stock productivity and abundance become high.

The predicament of many overexploited species worldwide is analogous to that of striped bass during the early 1980s. Whether other species will show the same positive response to conservation efforts is unknown. Examples exist of population recovery after curtailment of fishing mortality (e.g., North Sea plaice *Pleuronectes platessa,* Smith 1994; North Sea Atlantic herring *Clupea harengus,* Bailey and Steele 1992); however, other populations have failed to recover (e.g., California sardines [=Pacific sardines] *Sardinops sagax,* Ueber and MacCall 1992; decapod crustaceans in the Gulf of Alaska, Orensanz et al. 1998). Overharvesting can lead to major ecosystem changes (Dayton et al. 1995; Fogarty and Murawski 1998) that may inhibit recovery to a former state. However, the case history of Atlantic striped bass demonstrates the dramatic effect that fishery management can have and furnishes an encouraging example for restoration of other depleted fishery resources.

Acknowledgments

Successful fisheries management relies on dedicated individuals with long-term commitments to the resource. Striped bass management has benefited from the efforts of many such individuals. In particular, David G. Deuel of the National Marine Fisheries Service devoted nearly two decades of his career to handling many of the endless administrative details of funding, project management, and rule-making that laid the foundation for recovery of the striped bass stock. David also made significant and wide-ranging contributions to the

scientific debate on striped bass biology and management. We dedicate this paper to his memory.

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Appendix: Evaluation of Stocking Efficacy

Preliminary analysis indicates that hatchery fish composed 5–7% of the commercial striped bass harvest in Maryland in 1991 (P. J. Rago, unpublished analyses). More than 10% of commercial landings in the Patuxent River and nearly 30% of recreational landings in adjacent counties were hatchery fish, but stocked striped bass were infrequent in landings from other areas in Maryland. The Patuxent River received the greatest input of hatchery fish during 1985–1988 (USDOI and USDOC 1996). On the coast of Long Island, 3.5% and 2.4% of fish caught in autumn of 1991 and 1992, respectively, were hatchery fish released in Chesapeake Bay during 1985–1989 (Waldman and Vecchio 1996).

These statistics give some indication of the contribution of hatchery fish to the fishable stock; however the relative gain in resource recovery from stocking versus restricting fishing activity is a critical issue. In this appendix, we use a modified Leslie matrix model to evaluate the tradeoffs between manipulating stocking rate and manipulating fishing mortality to bring about positive population growth. The analyses assume equal reproductive value of mature hatchery and wild fish, and thus probably underestimate the relative benefits of reducing fishing mortality (Waldman and Vecchio 1996).

The basic Leslie matrix model has the form $\mathbf{A}\boldsymbol{X}_t = \boldsymbol{X}_{t+1}$ where $\boldsymbol{X}_t$ is a column vector of the population numbers at age $= (x_1, x_2, \ldots, x_K)^T$ and $\mathbf{A}$ is a square matrix of the form

$$\mathbf{A} = \begin{bmatrix} R_0 & R_1 & \cdots & R_K \\ S_0 & 0 & \cdots & 0 \\ 0 & S_1 & \cdots & 0 \\ \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & S_{K-1} & 0 \end{bmatrix}; \qquad \text{(A.1)}$$

R_i = number of female recruits produced per female of age i, and
S_i = fraction of individuals of age i that survive to age $i + 1$.

Equation (A.1) can be written in terms of standard fisheries parameters by defining R_i and S_i as follows:

$$R_i = \text{mat}_i \cdot \text{Fec}_i \cdot s_0; \qquad \text{(A.2)}$$

mat_i = fraction mature at age i,
Fec_i = Egg production of female at age i, and
s_0 = Average survival between the egg stage and age 0;

$$S_i = e^{-(\text{PR}_i F + M)}; \qquad \text{(A.3)}$$

PR_i = "partial recruitment"—the fraction of individuals in age-class i vulnerable to fishing mortality,
F = instantaneous rate of fishing mortality, and
M = instantaneous rate of natural mortality.

An interesting property of this model is the ability to estimate the finite rate of population growth, λ. The parameter λ corresponds to the dominant eigenvalue of the matrix **A.** The finite rate of increase can be derived numerically or approximated by iterative application of equation (A.1).

$$\mathbf{A}\boldsymbol{X}_t = \lambda \boldsymbol{X}_t, \qquad \text{(A.4)}$$

where $\boldsymbol{X}$ approaches ξ, the stable age structure of the population.

The average survival between the egg stage and age 0, s_0, is rarely known and is usually estimated by using the method of Vaughan and Saila (1976) as

$$s_0 = \frac{\lambda}{R_1 + \sum_{j=2}^{K} \prod_{i=1}^{j-1} S_i R_j / \lambda^{j-1}}. \qquad \text{(A.5)}$$

With equation (A.5) it is possible to estimate the average s_0 necessary to obtain a specified level of λ with a given schedule of reproduction and survival.

The effects of hatchery stocking on fish populations can be written in the form

$$\mathbf{A}\boldsymbol{X}_t + \boldsymbol{H}_t = \boldsymbol{X}_{t+1}, \qquad \text{(A.6)}$$

where $\boldsymbol{H}_t = (h_t, 0, 0, \ldots, 0)^T$ = the number of age-0 fish stocked at time t. The first element of $\boldsymbol{X}_{t+1}$ can be written as

$$x_{1,t+1} = \sum_{i=1}^{K} R_i x_{i,t} + h_t. \qquad \text{(A.7)}$$

The stocking rate h_t can be expressed as a proportional increase β in the average fecundity of the population. Equation (A.2) can be rewritten as

$$R_i^* = \text{mat}_i \text{Fec}_i s_0 \beta. \qquad \text{(A.8)}$$

Equation (A.7) then becomes

$$x_{1,t+1} = \sum_{i=1}^{K} R_i^* x_{i,t}. \qquad \text{(A.9)}$$

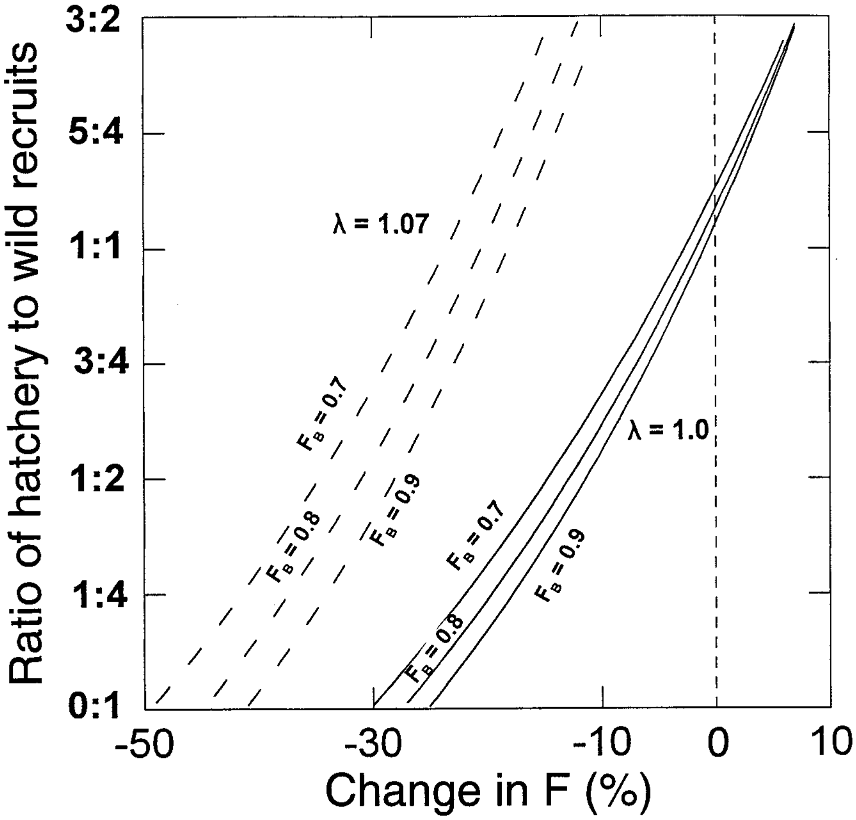

FIGURE A.1.—Tradeoffs between reducing fishing mortality (F) and increasing hatchery stocking rates to attain desired rates of population growth. Lines are shown for three fishing mortality rates (F = 0.7, 0.8, 0.9) that might have prevailed when the population was declining by 10% per year. Solid lines represent combinations of stocking rates and reductions in F that would stop the decline but not lead to population growth ($\lambda = 1$). Dashed lines represent combinations necessary for population doubling within 10 years ($\lambda = 1.07$).

Fractional changes (α) in the underlying mortality can be evaluated as

$$S_i = e^{-(\mathrm{PR}_i F\alpha + M)}. \quad \text{(A.10)}$$

Equations (A.1)–(A.10) provide the basis for evaluating various hypotheses related to population growth and the necessary changes in fishing mortality and hatchery stocking rate. Consider a baseline period in which the population is declining at some rate, λ_b, and the fishing mortality is F_b. The average s_0 occurring under these conditions can be solved by using equation (A.5). Now suppose that it is desirable to increase the population growth rate to some new target level, λ_T, by manipulating fishing mortality or stocking rate. By substituting equations (A.8) and (A.10) into equation (A.5) and rearranging terms it is possible to determine the per capita change in reproduction (β) necessary to obtain the target level of population growth λ_T for any specified change α in fishing mortality.

$$\beta = \frac{\lambda_T}{s_0\left(R_1 + \sum_{j=2}^{K}\prod_{i=1}^{j-1} e^{-(\mathrm{PR}_i F\alpha + M)} R_j / \lambda_T^{j-1}\right)}. \quad \text{(A.11)}$$

In summary, the steps for evaluating the tradeoffs between hatchery stocking and changes in fishing mortality are as follows:

(1) Specify λ_b and F_b during the baseline period and use equation (A.5) to obtain s_0.

(2) Specify a desired target rate of population growth λ_T.

(3) Evaluate the per capita increment in reproduction (i.e., the stocking rate β) necessary to attain λ_T for a given change in fishing mortality α by using equation (A.11).

The results of such analyses applied to Chesapeake Bay striped bass show that substantial stocking effort would have been required to offset the fishing mortality that probably prevailed during the decline (Figure A.1). The solid lines to the right in Figure A.1 present combinations of fishing mortality reduction and stocking effort necessary to stabilize a population at its current level ($\lambda = 1$), assuming equivalent survival of hatchery and wild fish. For example, reducing fishing mortality by 10% and stocking one hatchery fish for every two wild recruits (0.5 hatchery fish per wild recruit) would stabilize the population. The dashed lines to the left show that population doubling could occur without stocking by reducing fishing mortality by 40–50% or by reducing fishing mortality by 15% and stocking three hatchery fish for every two wild fish.

The number of hatchery fish implied by the above analyses is difficult to determine because estimates of absolute juvenile abundance in Chesapeake Bay have not been made. However the proportion of hatchery fish in landings provides the basis for a rough estimate. If 4.5 million hatchery striped bass made a 5–7% contribution to the fishable population in Maryland, then 70.5 million stocked fish would have been necessary to achieve a 1:1 annual hatchery contribution to recruitment during 1985–1993. A 16-fold increase in hatchery production would have been needed to achieve the same population level effect as a 25–30% reduction in fishing mortality. Because fishing mortality was reduced far more than this, the necessary increase in hatchery production would have been even greater to achieve a 1:1 ratio. Without reducing fishing mortality, hatchery stocking in excess of 1.5 hatchery fish per wild recruit would have been required for population doubling within 10 years (Figure A.1). A detailed economic analysis has not been conducted; however, these calculations suggest that the benefits of fishery conservation far outweighed the benefits of stocking.